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Russian Translation

Instrument for Relative Measurements of Direct Magnetic Fields

7N-35-TM

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136356

Radiotekh. i Elektr., vol. 1, No. 12, 1956, pp. 1515-1519

Abstract: An instrument is described which uses the phenomenon of nuclear magnetic resonance absorption for the relative measurements of weak inhomogeneous fields. The instrument contains an automatic trimming circuit. The maximum magnitude of the difference in the magnetic field intensities which is measurable is $\Delta H_{max} = \pm 5$ percent of the field to be measured. The measurement accuracy is $\pm(3-4)$ percent of ΔH. Measurements were performed at $H_o = 150$ Oe.

Introduction

It is often necessary to know the exact distribution of the direct magnetic field in a number of physical investigations and in solving certain engineering problems.

In the instrument to be described below, the measurement of the difference in the magnitudes of the magnetic field intensity at two points reduces to the measurement of the difference in the frequencies ω_{I_1} and ω_{I_2} of two high-frequency generators which are trimmed automatically at the frequency ω_L of the precession of the nucleus of the substance in the pick-off in the magnetic field to be measured.

As is known [1], when signal absorption is manifest, the value of the generator frequency is close to the Larmor precession frequency

(1) $$\omega_1 \simeq \omega_L = |\gamma| H_o$$

where γ is the gyromagnetic ratio.

An automatic frequency control circuit, in terms of the minimum signal to be controlled, is introduced in the instrument in order to make the generator frequency control automatic and in order to accelerate the measurement process.

An alternating field with amplitude H_m small in comparison to the signal absorption line width is superimposed on the H_o field level during the measurements. Hence, a periodic signal appears at the output and its first harmonic is discriminated by the phase detector. The rectified voltage of this component is used to control the frequency of the high-frequency generator. The magnitude and sign of the control voltage are determined by the magnitude and sign of the detuning $\Delta\omega = \omega_o - \omega_\Gamma$.

The instrument is not needed in the preliminary calibration and it permits absolute and relative measurements to be made with a high degree of accuracy and a small expenditure of time.

The instrument was developed to measure the injection field distribution (H_o = 150 Oe) of the electromagnet of the 10 milliard eV synchro-cyclotron of the Acad. of Sciences, USSR.

1. Description of the instrument

The instrument consists of three components of which two are fundamental and identical. Each fundamental component consists of a self-oscillator with a pick-up, a low-frequency amplifier, a phase detector with a filter and a reactance tube. The auxiliary component had an audio frequency generator, a mixer and a 'sign circuit'.

The block diagram of the instrument is shown on figure 1. The field pick-ups 1 are placed in the magnetic field to be measured. Each pick-up consists of an inductance coil of the tuned circuit of a generator with self-excitation 2 and of an ampoule with a paramagnetic substance within the coil. The pick-up is connected

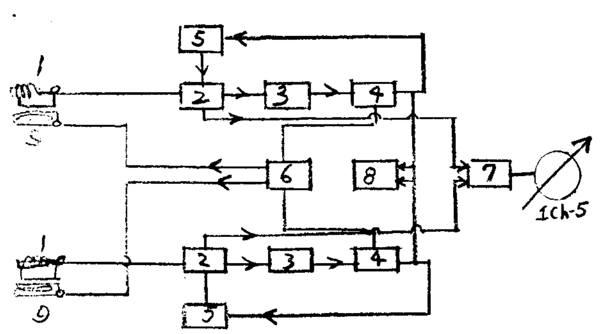

Figure 1. Instrument block diagram

to the generator 2 by a 20 m long cable RK-50 . A modulation coil 9 , to which a voltage from the audio frequency generator 6 is fed, is in series with the pick-up.

The nuclear resonance signal is detected in the grid circuit of the oscillator tube, is amplified by the narrow-band low-frequency amplifier w and presented to the phase detector 4 . A modulating frequency voltage from the audio generator 6 is also fed to the latter.

In order to increase the signal-to-noise ratio and to discriminate the voltage of the first signal harmonic, a narrow-band amplifier with a negative feedback circuit in the form of a double T -bridge tuned to an $f = 425$ cps frequency (pass-band $\pm$ 15 cps) is used. The audio frequency generator is tuned to the amplifier resonant frequency.

The phase detector output is connected to the control grid of the reactance tube 5 through a two-section RC filter. The filter serves to eliminate self-excitation of the locked automatic trimming system and to decrease the effect of interference. The generator frequency varies so that $\omega_T \to \omega_L$ depending on the magnitude and sign of $\Delta\omega$.

The steepness of the modulation characteristic of the reactance tube $\frac{\partial\omega_T}{\partial U_c}$ is ~ 7 kc/V at $f_o = 650$ kc ($H_o = 150$ Oe) and the frequency deviation is ~ 25 kc ($\pm$ 2 % f_o). The dependence $\Delta\omega_1 = f(U_c)$ is linear enough in this detuning range.

The high-frequency voltage of each generator proceeds through the cathode follower along a cable to the mixer 7 in which the modulus of the difference in the frequencies of both generators $|\omega_{T_1} - \omega_{T_2}|$ is discriminated. The magnitude of this difference is measured by a pointer frequency meter ICh-5 . The frequency-meter scale can be calibrated in ΔH or $\frac{\Delta H}{H}$ % units. The sign of the difference (the frequency of which generator is higher) is indicated by the zero-instrument 8 connected to the output of a circuit whose input receives the control voltages from the outputs of both the phase detectors. The zero-instrument full scale corresponds (for maximum sensitivity) to the ~ 0.25 Oe field difference.

Distilled water ($\gamma = 2.67 \cdot 10^7$ Oe/sec for protons) is used as the paramagnetic substance of the pick-up. A small quantity of $MnCl_2$ (concentration of the $MnCl_2$ solution $\sim 5 \cdot 10^{-2}$ molar) was added in order to decrease the relaxation time. The organic glass ampoule had a 17 mm diameter, was 40 mm long and the glass was 0.5 mm thick. The circuit quality was $Q = 120$. The pick-up and the modulation coil are housed in a rectangular brass box which serves as an electric screen (fig. 2)

Figure 2. External view of the field pick-up in the screen (scale in cm)

The high-frequency oscillator consisted of a single 6H9 triode tapped-capacitor oscillator with a grounded plate [2]. The magnitude of the amplitudes of the high-frequency oscillations and, therefore, the generator sensitivity were regulated by a potentiometer varying the magnitude of the feedback. Such a generator circuit possesses a number of advantages over other similar circuits: the presence of two terminals at the loop inductance with one grounded; the simplicity of regulating the sensitivity (the magnitude of the feedback) and one tube performs the function of a high-frequency oscillator, detector and low-frequency amplifier. A vacuum-tube voltmeter with a microammeter in the plate circuit is used to indicate the amplitude of the generator oscillations.

The low signal level and the high gain ($\sim 10^6$) required the use of a number of measures to attenuate the alternating current background: the tube plates were supplied from an electronically stabilized rectifier guaranteeing a $\sim$10 mV pulsation level; the heater circuits were supplied from a direct current source.

Only the audio generator voltage was detected at the phase detector output in the case of control signal absence. This voltage was fed to the grid of the reactance tube and is used as a reference voltage.. An additional phase shift relative to the modulating voltage appears when a signal voltage passes through the amplifier channel. A phase inverter is used to compensate this effect. The phase detector characteristic is linear in a large range of signal voltage values. A pointer instrument, which indicates the magnitude and sign of $\Delta\omega$, is connected into the phase detector circuit. Normal operation of the automatic frequency control system can be judged by its readings and in what part of the characteristic $\Delta\omega = f(U_c)$ is the operating point of the reactance tube found. Provided in the instrument is a toggle switch to lock the regulation circuit when tuning the instrument and the generator input in the automatic trimming band.

The instrument is formed as two separate blocks connected by a coaxial cable which can be tens and even hundreds of meters long. This permits relative measurements to be made between two points separated by a considerable distance.

2. Measurement accuracy

The error in measuring the difference in the field intensities at two points is determined by the error introduced by the regulation loop, by the instability of the circuit parameters and by the class of accuracy of the pointer instrument.

It is convenient to illustrate the instrument operation graphically (fig. 3) as a regulation system, where 1 is the reactance tube characteristic;

2 is the discriminator characteristic; $\omega_{\Gamma_{1,2}}$ are the generator frequencies for $U_c = 0$; $\omega_{p_{1,2}}$ are the frequencies corresponding to the resonance values of the $H_{p_{1,2}}$ fields; $\omega_{v_{1,2}}$ are the frequencies to which the high-frequency generators are tuned in the presence of the difference frequency $\Delta\omega = |\omega_{\Gamma_{1,2}} - \omega_{p_{1,2}}|$.

Although the discriminator intrinsically is the pick-up substance, i.e., the apparatus giving a signal on the presence of the detuning $\Delta\omega$, its magnitude and sign, all the elements of the circuit from the pick-up to the phase-detector filter inclusively are understood to be the discriminator in this case.

The regulation error for joint operation of two automatic trimming systems can be determined from figure 3:

$$\delta\omega = \pm \frac{a - 1}{p_2} \Delta\omega \qquad (2)$$

where $p_{1,2} = 1 + |k_{d_{1,2}} \cdot k_{rt_{1,2}}|$ are the regulation coefficients of each system; $a = \frac{p_2}{p_1}$; $k_{rt} = f\left(\frac{\Delta\omega}{U_c}\right)$ is the transfer coefficient of the reactance tube; $k_d = f\left(\frac{U_c}{\Delta\omega}\right)$ is the discriminator transfer coefficient.

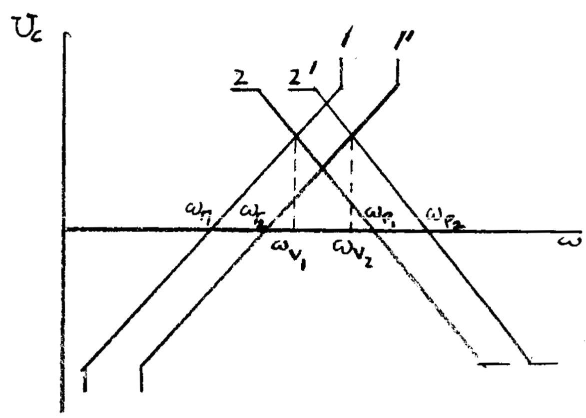

Figure 3

The expression (2) determines the regulation coefficient p_2 for admissible values of a and given $\delta\omega$ and $\Delta\omega$. According to the condition, the regulation erro should not exceed $\pm 2\%$ and $\Delta H_{max} = \pm 5\% \ H_o$.

If the difference in the magnitudes of the regulation coefficients p_1 and p_2 is not larger than 10 % , then the regulation error will not exceed a given magnitude for $p_2 = 60$ and $p_1 = (0.9\text{-}1.1)p_2$.

In order to explain the regulation accuracy, a family of characteristics $\delta f = \varphi(\Delta f)$ was recorded for several values of the high-frequency voltage on on the generator circuit (U_{ko}) (fig. 4). The nonlinearity of the characteristic $\delta\omega = \varphi(\Delta\omega)$ is related to the dependence of the k_{rt} and k_d on $\Delta\omega$. It follows from figure 4 that the regulation error for $U_{ko} = 1.6$ V is 1-2 % of the quantity to be measured over the whole detuning range $\Delta\omega(p_1 \sim p_2 = 100\text{-}60)$.

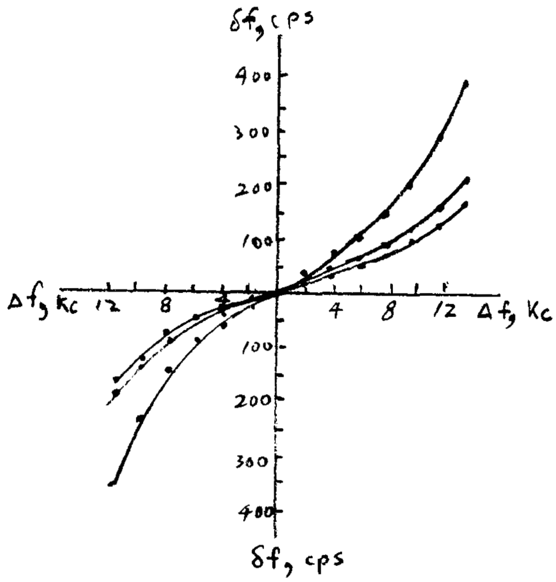

Figure 4. Dependence $\delta f = \varphi(\Delta f)$: 1 - for $U_{ko} = 1.9$ V ; 2 - $U_{ko} = 1.7$ V; 3 - $U_{ko} = 1.6$ V.

An analytic expression is cited in [3] for the transfer coefficient of a pick-up - generator system which defines the fundamental factors influencing regulation accuracy.

Mechanical tuning of the high-frequency generator displaces the curve 1 (fig. 3) along the frequency axis.

The small variable condenser of the generator loop alters the frequency by $\pm 5\ \%$ with the regulation loop open, which extends the measurement limits to $\Delta H_{max} = \pm 5\ \%\ H_o$, where $H_o = 150$ Oe .

When the magnetic field is stable, the whole variation of ω_T (the plate voltage variation, the high-frequency cable parameters, the noise voltage presented to the discriminator along with the signal, etc.) causes a signal detuning which returns the frequency to its previous value (fig. 3). The effectiveness of such field stabilizing action on ω_1 is determined by the regulation coefficient p . Consequently, the measurement errors caused by the variation of the tube regions and by the instability of the circuit parameters are negligibly small.

The error of the measuring instrument - the pointer frequency meter, ICh-5 - is $\pm 2\%$ of the nominal scale value. The frequency-meter sensitivity, referred to ΔH, is $\pm 0.4\%$, i.e., lies below the measurement errors. Hence, the usual measurement error at $H = 150$ Oe is $\pm(3\text{-}4)\%$ of the magnitude of the field difference ΔH to be measured. The absolute measurement accuracy is of the order of $\pm 0.01\%$.

3. Instrument operation

The instrument was tested in measuring the spatial distribution of the magnetic field in the gap of one of the blocks of the electromagnet of the synchro-cyclotron of the AN USSR. Shown on figure 5, as an illustration, is one of the curves obtained (a). The check of the results obtained was made by comparison with the field distribution curve of this same electromagnet block recorded by using a ballistic galvanometer (curve b). Both curves are in good agreement.

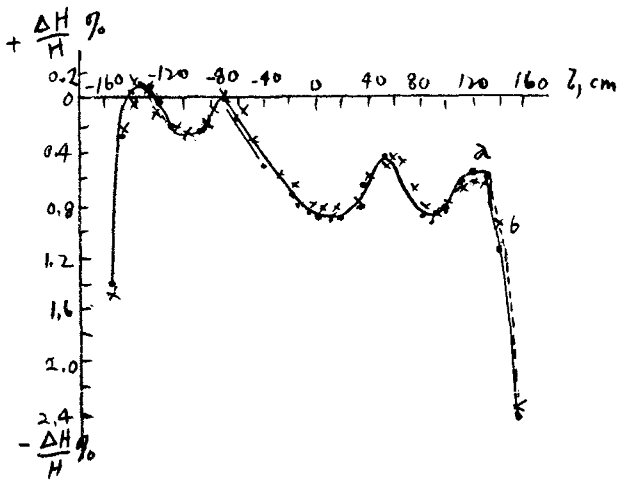

Figure 5. Field distribution curves of one of the blocks of the synchro-cyclotron electromagnet recorded: a - using the instrument described; b - a ballistic galvanometer.

Testing of the instrument showed that a significant level of acoustic and electric noise does not affect the measurement accuracy and speed. The instrument guarantees a higher measurement rate than the ballistic galvanometer.

Conclusion

The instrument described above can be used in laboratories as well as in industry when a considerable volume of measurements must be made.

An increase in measurement accuracy can be obtained by using a reading instrument of the 0.5-1.0 class and by increasing the transfer coefficient. These measures can guarantee an accuracy of up to $\pm(0.5\text{-}1.0)\%$ ΔH.

The operating principle of the instrument (automatic frequency control of the generator according to the field intensity magnitude at the pick-up location) permits measurement results of the spatial field distribution, its time characteristics, etc. to be recorded automatically on a measuring chart.

The authors thank Prof. V. A. Petukhov for a number of valuable remarks while discussing this work and A. N. Zinevich for participating in production of the instrument.

June 1, 1956

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